International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 02 - Issue 11 || November 2017 || PP. 01-14

An Overview 3-D Geological Modelling Part I- Basics of 3-D Geological Modelling

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Abstract: The paper present an overview of the Basics of 3-D Geological Modelling in the context of research and modelling practices. It highlighted the basic of modelling, model types, its representation, diverse fields of applications and the Limitations of 3-D Geological Modelling. Various types of modelling data, the needs and the process of data pre-processing (data consistency & validation), are discussed in detail. The different modelling approaches to accomplish the modelling task, and the corresponding thought process involved in the approaches is elaborated. The different software available and their modelling and functional capabilities are overviewed.
Keywords: Data preprocessing, Geological Models, modelling approach, Modelling Software.

I. Introduction to Geologic Models

The heterogeneous data gathered during site investigations, is not a straightforward information pool for decision makers and the other end-users, as it needs to be reinterpreted by experts for specific purposes. The homogenization of multiple, mostly analogous, data sets, and their subsequent integration into the modelling process to form a 3-D structure model, adds value to the existing database information. One of the advantages in a 3-D modelling system is the common visualization of multidisciplinary information sets and their spatial relation in three dimensions, allowing new insights into the nature of the subsurface. It enables to visualize the geological subsurface in terms of the lateral distribution and thickness of each geological unit as well as the succession of the geological units. [17].

As per the Commission of the International Association for Engineering Geology and the Environment (IAEG) working on the *'Use of Engineering Geological Models'* (C25), the engineering geological models for geotechnical project are an essential tool for engineering quality control and provide a reliable means of identifying project-specific, critical geological issues and parameters. Models should form the basis for designing the scope, method and assessing the effectiveness of site investigations.According to C25 the term model in engineering geology is hypothesized as *an approximation of reality created for the purpose of solving a problem. It is an approximation of the geological conditions, at varying scales, created for the purpose of solving an engineering problem.* C25 considers that engineering geological models encompass both “geological models” and “geotechnical models”; they involve understanding geological concepts as well as defined geotechnical data and engineering requirements [19].According to C25 the different fundamental methodologies used for the generation of these model types are:

a) ***The conceptual approach*** is based on understanding the relationships between engineering geological units, their likely geometry, and anticipated distribution. This approach, is based on concepts formulated from knowledge, experience, and are not related to real three-dimensional (3-D) space or time. A fundamental purpose of the conceptual model is to identify the credible engineering geological unknowns present, which can be targeted for investigation, to assess their potential hazard to the project. The success of this approach is strongly dependent on the knowledge and experience of experts involved in creating the models.

b. **The observational engineering geological approach** is based on observations and data from project-specific ground investigations. These ground investigations should be designed using conceptual models and should target the uncertainties identified by them. The observational engineering geological model is created from the site-specific ground investigation information, are constrained by observational and measured data, and should present geological information in space or time. They should verify or refine the conceptual engineering geological model. In particular, they should focus on potential engineering issues identified in the conceptual engineering geological model. Observational engineering geological models are particularly relevant at the engineering design stage. The observational engineering geological models can take a wide variety of forms: graphical borehole logs (one-dimensional), engineering geological cross sections and maps (two dimensional) and spatial engineering geological models (three dimensional) either as solid models (e.g. [26]) or, increasingly, digital models [6].

c. **The Analytical Model -** The analytical model requires considerable simplification of the observational model and, therefore, significant engineering geological judgment is required to ensure that representative ground conditions, including geotechnical parameters and boundaries, are adopted. The aim should be to focus on a model that captures the essence of the engineering design issues, but is still robust enough to illustrate the inherent engineering geological variability.

II. Geological Modelling Process

The spatial data are used to create a 3-D geometry model, Geometry modelling involves two steps – first the development of a suitable geometric representation of the fundamental geological "framework," and subsequently the subdivision, or "discretization" of this framework to provide control for the analytical computations within the numerical models used in the predictive modelling. Geometrical representation of the geological framework, define and control the spatial distribution and propagation of rock-properties required by modelling [24]. Framework definition is accomplished by applying a variety of data types, including,

i. Borehole and isolated sample data,
ii. Surfaces (Triangle, Quadrilateral, NURB- non-uniform rational B-splines),
iii. 2-D grids and meshes, and
iv. A variety of iso-volumetric models created from multiple surfaces, cross-sections, and grids and, meshes.

2.1 Stratigraphic Models

Sedimentary geologic environments is modelled by creating surfaces defining the strata interfaces, stacking the surfaces in stratigraphic succession, and subsequently defining the zones between surfaces as geologic units. Careful review and editing of all surfaces is required to allow for areas of erosion or non-deposition & mutual intersection. The Construction of individual surfaces generally proceeds by one of three methods:

i. Using the borehole observations to create a triangles defining a surface,
ii. Applying surface generation and contouring procedures to borehole observations, or
iii. Developing a series of interpretive cross-sections between boreholes.

2.3 Non-stratigraphic models

Regions with complex geological structures, or without layered sequences, are developed by a series of complex shapes enclosing volumes derived from a series of interpreted cross-sections with common bounding surfaces. An alternative approach begins with an entire regional volume and then progressively subdivides it into regions with a series of intersecting surfaces that represent major discontinuities such as shear zones or faults. A limitation of this approach is that all geometry must define closed, solid volumes. Non-manifold geometry, such as a fault plane that terminates within a volume or a well bore, which is a zero volume line, cannot be represented. Faults add anisotropy to property distributions required by the numerical models. Vertical, or nearly vertical, faults and nearly horizontal thrust zones can be defined by adding additional surfaces to the existing stratigraphic models

2.4 Surface-based approaches

Geomodelling methods with Surface-based approacheshave the ability to compactly represent complex shapes in 3-D. From a mathematical standpoint, two main types of surface representations,viz. ***Parametric Surfaces*** and ***Polygonal Surfaces.***

The classically used representation in Computer Aided Design allowing convenient user interaction is parametric surfaces, which use polynomial or rational equations describing the surface geometry using parametric coordinates. In these approaches, discontinuities are addressed using one parametric patch per connected component (fault segment or continuous horizon inside a fault block). These surfaces need then to be truncated along discontinuities for graphical display and structural model queries.

Polygonal surfaces consist of a network of nodes connected by polygons. Mathematically Triangular surfaces have the properties of simplified meshes and conforms geological requirement without degeneracy to all types of geometry and topology (densely faulted domains, complex intrusive or erosive contacts, etc.), and can be adaptively refined where needed. Whatever the mathematical model retained, surfaces should honour representational validity rules (finite extension, orientability, non-intersection and geological validity rules non-intersection of rock boundaries, absence of dangling surface edges except for laterally dying and synsedimentary faults.) [5].

2.5 Volume-Based Approaches

Isolated surfaces are the 3-D counterpart of the spaghetti format in GIS; they do not necessarily bound well-defined volumes. The simplest volume model is a Cartesian grid whose blocks are flagged depending on the geological unit they belongs. Geological interfaces if stair-stepped increases model resolution helps in improving model accuracy and increases the number of model parameters. Adaptive Cartesian grids such as octrees may be used to more compactly represent structures by using local refinement in areas of high geometric complexity. However, such Cartesian representations do not directly represent fault offset nor locally varying anisotropy related to rock deformations.

Stratigraphic (corner-point) grids address both problems by conforming grid blocks to most structural interfaces. Construction is often achieved by extrusion of a 2D grid vertically or along so-called pillars, which define a direction field tangent to the main faults. Alternatively, grids may be warped to conform to structural interfaces. These grids have become standard in the modelling of underground reservoirs. They approximate the coordinate transform to apply geostatistical methods in depositional space, thereby accounting for depositional heterogeneities. In addition, they offer a support to finite-volume based flow simulation. However, conforming to geological structures generally yields non-orthogonal grids, which may introduce distortions in geostatistical models and discretization errors in flow simulation. Moreover, from a practical standpoint, these grids are very difficult to create in the presence of low-angle faults and sub horizontal fault contacts and hence only covers a subset of the volume of study. These shortcomings make corner-point grids difficult to apply at basin scale and to igneous and metamorphic formations.

Boundary representations, or sealed geological models, stitch surfaces together to define rock volumes. The full structural complexity can therefore be captured by these models, which have been widely used in geomodelling. Analytical properties may be defined within each region to support numerical integration with the boundary element method. When a higher level of detail is needed, conformable meshes are generated within each region. Among these, tetrahedral meshes are simple and can in principle adapt to complex boundary geometries; as for triangulated surfaces, tetrahedral level of detail can be variable in space to honor data or geological features. In spite of recent advances in mesh generation, accounting for complex constraints such as sharp geological contacts, thin layers or fracture networks is difficult to represent.

One way to address these mesh generation problems is to use implicit surfaces or level sets to represent geological structures. In this representation, some structural interfaces are equipotential surfaces of some 3-D scalar field f(x,y,z). Several approaches have been described to build the 3-D scalar field f(x,y,z) from a set of data points, using radial basis functions, dual kriging with polynomial drift, or discrete interpolation on Cartesian grids or tetrahedral meshes. As compared to surface-based structural modelling, implicit methods are preferred because they provide some built-in model consistency rules, and do not rely on data-to-surface projections, which raise a number of problems in classical approaches [5].

The conventional 3-D volumetric data models include constructive solid geometry (CSG), 3-D-raster, Octree, Tetrahedral Network (TEN), Tri-Prism (TP), Generalized Tri-Prism (GTP), Geocellular, etc. [23], [25]. 3-D vector data models, which describe solid volumes in terms of their enclosing surfaces, emphasize on the surface representation for the spatial objects. The conventional 3-D vector data models include Boundary Representation (BRep); Wire Framework and Non-Uniform Rational B-splines (NURBS). 3-D mixed data models use two or more vector/volumetric data models to describe one geo-object at the same time. The conventional 3-D mixed data models include BRep-CSG (Constructive solid geometry), GTP-TEN and BRep-GTP-TEN. 3-D integrated data models firstly apply various single data models to describe different types of spatial objects respectively, and then integrated them into a unified 3-D space to fully represent multiple types of spatial objects. The conventional 3-D integrated data models include CSG+ TIN (Triangulated Irregular Net) + GTP, BRep + TEN + GTP and object-oriented data model [31].

III. Applications Of 3-D Geologic Models

3.1 Geological understanding

One of the major application is geological understanding of the local geological structure, was not possible using other commonly used methods. The modelling is Preference for highly variable subsurface conditions at the project site [8], and the site characteristics with geologically complex area / faulted Ground / not well-understood geology [1].3-D geological models can express, verify and modify conventional geological cognition/judgment/knowledge. It explain and portray complex geology in understandable formats [2]. 3-D lithologic, stratigraphic, and textural models can be constructed which resulted in several new interpretations regarding the thickness, extent, and spatial 3-D distribution of the important geologic units in the Basins [7]. The area and volume of each defined geological body can be calculated and further analytical functions allow integrating and visualizing hydro-geological, engineering properties and physical or other parameters for each mapped units. 3-D model of geometrical bodies can be produce representing different lithologies by a geostatistical interpolation of the input data [15].

3-D geological modelling is being used for analysis of the subsurface geological characterization involving both geometrical structure and various parametric properties [31]. The digital 3-D attributed model are created by rigorous use of geological, geotechnical and geophysical data, geological knowledge and statistical methods [2]. Attribution of physical parameters (density, magnetic susceptibility) to each representative lithology of the model can be used for computation of the 3-D gravity or magnetic contributions of the model [15]. Contoured or gridded surfaces of tops, bases, thicknesses and volumes of single or combined geological units (including artificial ground) [6]. The 3-D Geological Modelling focuses on different types of visualization and predictive 3-D mapping but also provides all types of virtual cross-sectioning and predictive calculations of hydro-stratigraphical units and apparent validity inspections [17].

The 3-D spatial geological model can be interrogated using simple tools available in the software to produce,

- Horizontal slice maps at any depth and vertical cross-sections in any orientation [6].
- Synthetic logs and cross-sections at user-defined locations; /Contoured surfaces; Isopachytes of single or combined units; / Domain maps- Sub- and supracrop maps [6].
- A fully attributed Generalized Vertical Section (GVS). This forms the basis for engineering geological, hydrogeological and mineral potential classifications [6].
- Virtual sections can be calculated in highly variable positions and can be combined with subsurface and surface topographic information. The processing of such horizontal and vertical virtual sections gives a very precise positioning of distinct units or structures within the spatial model, especially of geotechnical and remediation applications. Thus it is also possible to analyse the subsurface, by creating geological maps, thematic maps, user defined cross-sections, horizontal slices in any elevation and synthetic drill holes [17].

Advantages of detailed, coherent ground model are, better knowledge of the ground conditions, more control, better the assessment of risks for construction, safety, constrain design and the final costs [1]. The integration of geoscientific data within a single 3-D model, and the ability to display and query these data, are significant advances for project decision [9]. The interpreted geological data pool can be used to develop management strategies for a wide range of sustainable ground-related issues. A detailed geo-scientific knowledge of the subsurface is essential for sustainable urban management and strategic planning, in terms of revitalization of contaminated sites, groundwater protection, and assessment of engineering conditions, mining resources, and the preservation of archaeological sites. The high-resolution 3-D models can be used for predictive application in the field of hydraulic modelling, environmental and geotechnical investigations. Digital 3-D subsurface models provide decision support tools for, planners and strategic decision makers. Visualization and analysis of the subsurface, by the expert geologist, - in order to deliver an easy-to-understand decision support system for policy and decision makers involved in sustainable regional planning [17].

The models can be kept in a dynamic form; such that each newly gathered piece of geo-scientific information, e.g. new drillings, can be added to the existing structure-model basic data set and the model can be modified according to this new information [17]. The models benefit from continuous validation and upgrading of the underlying database, as well as the production of regional syntheses, integrating geological, geophysical, and geochemical models in a single platform. It is helpful to catalyze the development of knowledge by easily integrating data under a common format; and preserving the data in a unique archiving platform where it can easily be shared, seen, and analyzed [9]. Various interpretive maps can be easily produced and updated with availability of new information and can be customized for specific needs [2].

3.2 Diverse Fields of application.

1. The multidisciplinary approach used in 3-D integrated geological modelling demonstrates its usefulness as a regional interactive exploration tool, allowing the use of various criteria to constrain and refine queries. [9]. The 3-D model can be used to quickly generate synthetic lines of section or synthetic borehole logs, to predict ground conditions at a particular point or on an alternative route alignment. It has also identified gaps in the dataset, assisting in the planning of continuing ground investigation [1].
2. Integrated investigation strategies of contaminated sites [17]. Identification, assessment, and remediation of large-scale groundwater contamination require a detailed knowledge of the heterogeneous geological structure to predict the fate and pathways of contaminants and their potential interaction with, e.g., surface water [30].
3. Management of groundwater resources, monitoring of water quality and all related environmental issues Assessment of location, thickness and capacity of aquifers and aquitards [17]. The conceptual

method consist of GIS-based ''Spatial 3-D-Model'' with emphasis on 3-D geological modelling and prediction of groundwater flow and transport for an integrated environmental risk assessment [30].

4. The geologic factors affecting conductivity and storage properties of the aquifer system for characterization of groundwater flow can be assessed. A 3-D portrayal of sediment texture (3-D Subsurface Mapping of Textural Classes) developed from the 3-D lithology model can help to characterize grain-size variations of the aquifer system [7].
5. The development of regional hydrogeological frameworks to serve as the basis for understanding groundwater, geological hazards, and natural resources [11].
6. The main sectors using 3-D geological models include Water, Wastewater, Waste Disposal, Contamination and Management, Hydrocarbon, and Carbon Capture and Storage, Land-Use Planning and Local Decision Making, Civil Engineering and Infrastructure, Archaeology, Mineral Resources (exploration), Research and Education and Outreach [2].

3.3 Specific Engineering Applications

The geological understanding developed through specifically built 3-D model can be utilized for engineering application e.g.

1. The ground characterization for tunneling in soft soils: The engineering requirements was to determine the volumes of each soil type to be encountered and its geotechnical properties, water pressures and surface settlements determination. The requirement were satisfied with the 3-D modelling functions with extensive use of external associated routines. 3-D geotechnical models can be used for numerical calculations to verify the engineering feasibility with regard to overall stability of tunnel sections, landslide prone slope etc. [18].
2. Analysis of geomechanical TBM performance modelling and quantitative volumetric analysis of geologic units [8].
3. The selection of cost effective and safe foundation type was determined by the regional estimation of soil settlement, aided by geometrical modelling, visualization and geostatistical analysis [18].
4. The subsurface conditions and the ground- structure interaction information was acquired for foundation decision-making. The geological information (depth, extent, thickness of layers), geotechnical information (soil/rock engineering properties, unit weight, cone resistance), and information regarding the behaviour of the ground when subject to a change in equilibrium was modelled for foundation decision. The 3-D geological and geotechnical models provide the ground parameters to the soil mechanics models [18].
5. Preparation of Maps for tunnels or pipelines along the proposed design route [6].
6. Seismic risk Evaluation ,Engineering projects, Assessment of CO_2 storage capacity Assessment of geothermal potential (BRGM French geological survey)

IV. Modelling Approach

A wide range of software can be used for 3-D geological modelling. The methods and related software are based either on use of sophisticated statistical methods; or on traditional geological understanding [2]. For 3-D geological modelling, choose software and methods that allow significant geological control on the distribution and character of the substratum being depicted. Constrains should be applied for the basic unit distributions and the characteristics of the modeled properties [2]. Different 3-D modelling approaches are, geostatistically and constructive cross-section based interpolations (TIN - Triangulated Irregular Net Interpretation) [30].

4.1 Modelling approaches based on Geostatistical algorithms;

The methods for developing the property models typically involve geostatistical tools. Statistical methods of interpolation reflects additional information on spatial variation, but alone do not depict the complete spatial structure of specific depositional environments or geological knowledge, and so the value of this information is limited [2]. There are several software packages incorporating geostatistical interpolation techniques, e.g. 3-D GIS, EVS/MVS, Earth Vision and RockWorks, MOSYS modelling system, GeoModeller, Gocad, Multilayer-GDM (Geoscientific data model)BRGM, Isatis etc.

4.2 Modelling approaches based on Constructive cross-section (the TIN - triangulated irregular net interpretation)

The geometrical modelling of the ground in Cognitive modelling methodology GSI3-D is based on cross-sections derived from the geological map, boreholes. The software utilizes a digital elevation model, surface geological line-work and downhole borehole data to construct cross sections by correlating boreholes and the outcrops to produce a geological fence diagram. The software takes into account all structural geology features such as dip, dip directions, strike, hinge lines, axial trace, and geologic faults to build the geometry of geological units [28].

V. Modelling Data

Data requirement for modelling is based on specific modelling objectives and application. Several different modelling methodologies have been developed depending on the type of data available. These methodologies, accounts for the variety of available data models and their integration in a 3-D geological model (Multi-Source Data Integration). To enhance the practical utility and the effectiveness of 3-D geological models, along with the stratum lithology, components, and grade information of geological bodies, the expression of attribute-oriented information and semantic information in 3-D geological modelling can be used [27].

5.1 Geological Data

Geological data obtain from site investigation consist of,

- Punctual data like Well data (water wells, geoscientific and academic wells, and oil and gas wells), /Borehole data. The Borehole data consist of stratum lithology/stratigraphy data, stratigraphic contacts.
- Details of structural geology features such as interfaces and orientation data (dip, dip directions, strike, hinge lines, axial trace, and geologic faults). Surface traces of faults.
- 2D cross-sections geological map (digital geological cross sections), historical maps, and archaeological subsurface data, digital thematic maps topographical, geological, hydro-geological maps, structural geology maps, digital terrain data, DTM of appropriate resolution [17].
- 3-D surfaces of formation bases, Isopachyte maps for formation [1].
- Line data such as rivers and creeks, and polygon data and outcrop data [30].

5.2 Geophysical Data

The 3-D geological models can be developed with an internal geometrical consistency, compatible with available geophysical data (magnetic, seismic, gravity etc.), and integrating the geological knowledge [15]. The modelling combines geological knowledge (surface geology) and geophysical surveys measurements (gravity data- ground-based and airborne gravity coverage, and a deep seismic reflection profile density, magnetic susceptibility) to model the 3-D geometry.The 3-D geophysical data such as resistivity, seismic, gravity or magnetic, GPR (Ground Penetrating Radar) etc., obtained from geophysical investigations and the conventional geological data along with the structural cross sections and the structural maps can be integrated together to develop 3-D model of the structure.

5.3 Physical Parameters

The geotechnical database for lithology characterization with parameters such as, unit weight, porosity, water content, friction angle, cohesion, permeability coefficient, and friction ratio i.e. attribute information of can be modelled over the geological bodies. In situ and laboratory test results such as Cone Penetration Tests (CPTs), vane tests, dilatometer, & pressiometer tests, Physical & chemical property parameter, hydrochemistry (contaminants) monitoring data can also be used for property modelling.

VI. Data Management

Integrating, homogenizing, visualizing, analyzing and storing all these differing data sets in one database management system, ready-to-use for the end-user groups, enables the cost and time for planning individual campaigns to be reduced. [17]. Digital geospatial databases allow many different types of geological data to be stored together, so that the user has a visual interface to all of the data collected for an area. Digital database offers considerably improved data retrieval, database searching, archiving and remote accessibility compared with conventional paper-based methods. This digital database will be input for modelling. The large amount of geological and geotechnical data expected from investigation works required an organized structure for data management, -evaluation, -analysis and –visualization to support decision making processes.

Because most geoscientific data are spatial in nature (i.e. specific to a given location) GIS are now widely used. GIS has evolved as a computer cartographic system, which is defined as ‘an information management system for organizing, visualizing and analyzing spatially orientated data. The, data collected from these investigation works can be compiled in a Geographic Information System (GIS) providing a geo-referenced database. In its original guise, GIS largely dealt with 2D data that were mapped onto the Earth’s surface. However, it was recognized that to deal with volumetric spatial information or 3-D geometries from subsurface data, a 3-D GIS or a GSIS (Geoscientific Information System) was required. Majority of software are with RDBMS software interface where data can be better managed with ease.

VII. Data Pre-processing

The quality of the model is affected by the quality & density of the data. Different data preprocessing means are applied ensure data quality used for modelling. Data pre-processing includes collecting, structuring and reinterpreting data in order to build a consistent dataset [12]. The reliable, usable and validated data are selected for the 3-D geological model reconstruction [12]. The interpreted and validated interpretative data and observational data has to be used for modelling. Interpretation can be compared with that of its nearest neighbours, as a check on the consistency of the interpretation [21]. The validity of borehole records and their interpretations can be assessed objectively, imparting greater confidence of reliable and representative borehole data. In addition, the methods are adopted for providing a means of objective identification of data that should be excluded [1].

Each borehole records can be examined in the 3-D context of surrounding data and interpretations [1]. The deepest of multiple, closely spaced and equally reliable boreholes can be selected for coding. Borehole selection should be independent of any pre-conceived geological model but quality and reliability criteria may be applied [6], also even distribution of good-quality borehole data should be ensure [10].

Initial Data Consistency Analysis is needed to be carried out. Data Pre-processing ensures that all data are considered in their correct position in 3-D space. All the data is check for its true coordinates, accurate geological description, good georeferencing, etc. Data is check for the data accuracy during the compilation of the databases, and statistical methods are use (e.g., histograms, scattergrams, and variance and covariance values) to discriminate the abnormal data before beginning the actual 3-D geomodelling process [4].

The mesh of consistent cross-sections should be used. It should validate the genetic aspects of landscape evolution envisaged by the geologist [17]. The geological data, representing lithological and stratigraphical characteristics and geological structures, should be validated by reference to genetical and morphological rules and perceptions [17].

Some tailor-made tools can be been written to manipulate, control and validate the data through an adapted interface including a visual comparison of logs of neighbouring data [12]. To utilize the geological data of different types and qualities and to maintain the data consistency, data Integration architecture can also be design [29].

Few software itself ensure data and geology consistency during modelling procedure e.g. 3-D GeoModeller (BRGM-Intrepid Geophysics) is use to,

i. Ensures that the model consistency with known geological relationships of the area in 3-D [11].
ii. To input of derivative geophysical data and geological concepts as guides to the geological modelling [11].
iii. Provides geophysical forward and inverse modelling to check for geophysical validity [11].

VIII. Modelling Approach

8.1 Geostatistical algorithm based Modelling

The distinctive lithologic classes can be used to construct a 3-D model of lithologic variations within the basin by extrapolating data away from drill holes using a suitable algorithm e.g. nearest-neighbor approach (3-dimensional gridding process). Interpreted drill-hole lithologic data can be numerically interpolated between drill holes by using a cell-based, 3-D gridding process (such as the RockWorks 3-D modelling software package - Rockware Earth Science and GIS software: www.rockware.com). A solid modelling algorithm can be used to extrapolate numeric codes that represent a lithologic class [7]. A strength of the 3-D gridding process is that the interpolated data in the resulting 3-D grid have the appearance of stratigraphic units, with aspect ratios that emphasize the horizontal dimension over the vertical. In addition, the method preserves the local variability of the lithology in each drill hole with no smoothing or averaging. Thus, where data are abundant, local lithologic variability is incorporated [7].

The single-stepped numerical modelling methodology requires a high concentration of boreholes, which are evenly distributed for each surface to be modelled [21]. The limitation of the type of numerical interpolation is the sensitivity to the distribution of the data, where values from an isolated drill hole tend to extrapolate outward to fill an inordinate amount of the model area. The effect is particularly noticeable where a small number of deep drill holes are interspersed with shallower holes. Data from the deepest drill holes in this case tend to over extrapolate over the entire model area. [7]. The uneven and spotty distribution of geological drilling information is one of the major obstacles in regional modelling with automatically contoured distribution and thickness [30]. The geostatistical-based interpolation of geo logical layers requires sufficient statistical borehole coverage [30]. With depreciating amounts of borehole data intersecting each succeeding lower layer the results achieved with a single-stepped numerical workflow become increasingly inadequate [21]. Another limitation of this method is that it is purely deterministic and data based. Alternatively, it may be possible to use a stochastic approach where the drill-hole data are used as a guide to predict subsurface lithologic variability. Such an approach would have the benefit of being able to incorporate depositional process

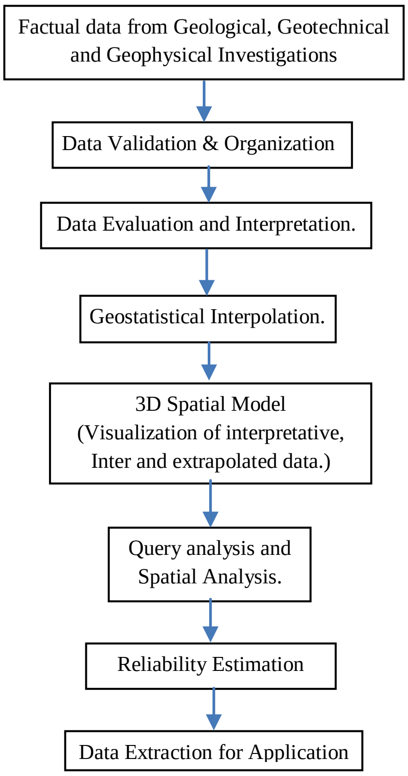

Fig.1. Conceptual Work Flow -Geostatistical Method

and facies relationships by evaluating the tendency of specific lithologic units to be adjacent to each other in specific geologic environments. For the large-scale nature of the study area, the presence of multiple depositional environments, and resource limitations, stochastic modelling approaches can be not applied. Faults cannot be explicitly included in the creation of the 3-D lithologic model, owing to the limitations of the geostatistical software package. However, the interpolation methods used produce lithologic variations can approximate fault truncations of lithologic units where data density is high [7].

Statistical methods of interpolation reflects additional information on spatial variation, but alone do not depict the complete spatial structure of specific depositional environments or geological knowledge, and so the value of this information is limited [2]. Interpolation between widely spaced filed observations requires geological knowledge to successfully replicate actual geological environments [23]. In combined use of cognitive and geostatistical interpolation method, the reference boundaries of lithostratigraphic units, obtained from the geological maps, locally modified from the boreholes data can be used to constrain the interpolated surfaces, and to limit the interpolations to the zones of different units [22]. Thus improving the quality of modelling.

8.2 Constructive cross-section based (knowledge-driven)

Modelling methodology such as GSI3-D allows the modelling of the distribution and geometry of sedimentary layers, stratigraphical situation as well as the geological history by knowledge-based control of the modeller, which is highly needed for heterogeneous aquifer systems [30]. No prior assumptions need be made about the local geological structure.

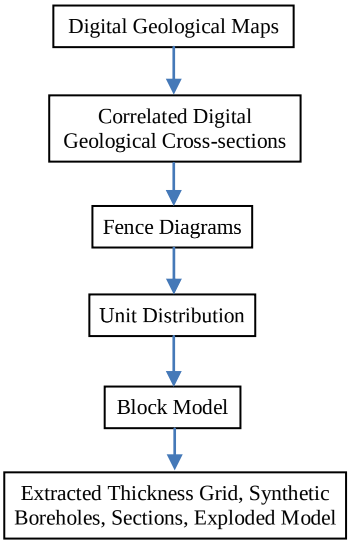

Fig.2. GSI3-D Workflow

The modeler controls the detailed configuration of each modelled surface, not by modelling algorithms within the software [1]. A cognitive interpretative approach can be used to create traditional geological maps to incorporate possible geological features for areas with the sparse or uncertain data.The software provides the modeller with the ability to connect areas in the model, where there is either only partial data coverage or where the geometry of the geological units is poorly understood [21]. The method can reproduce surfaces (faults and stratigraphic horizons) that not only honoured the data but also were also geologically reasonable even in areas where the data was sparse or uncertain [21]. The constructive and "knowledge-driven'' 3-D modelling allows the prediction of vertical and horizontal sections, visualization purposes, volumetric calculations of distinct sedimentary units.

The lithostratigraphic classification of the sedimentary succession within a consistent regional stratigraphic framework is more helpful than a pure grain-size or lithology-based approach. The lithostratigraphic approach in construction of 3-D geological models gives better results than only a pure grain-size or lithological-based automatically contoured approach. This statement is valid for most Quaternary sediments and artificial cut-and fill structures [30].It must be stated very clearly that the mentioned restriction depends on the specific geological situation. The advantages of geostatistically based modelling are high if the coverage of borehole data is sufficient. The insufficient density of borehole data is a function of the complexity of the subsurface. Therefore, the application of 3-D subsurface models, on local or regional scale, has to be completed by knowledge-based control, as much as possible [30].

The subsurface data available is normally very limited. Some basic geological, limited number of boreholes or probing data, rarely supplemented by geophysical data, is generally available for the modelling of the subsurface in civil engineering projects. To create a model of the subsurface from this limited amount of data requires the availability of expert knowledge. However the correctness of the model whether on paper or in a program cannot be assessed, because of the limited amount of data available and the heavy influence of expert knowledge/judgement on the final model. The statistical analysis of the relative uncertainty with GSI3D cannot be done inside the software package. Due to the plausibility-checked cross-section network, as well as additional information from 2D mapping and expert-driven interactive remodelling, the statistically based uncertainty of information is therefore difficult to estimate [30].

8.3 Combine Approach

The modelling methodology combining cognitive and numerical modelling can be developed to avail the advantages of both systems and to overcome the problem of having an uneven distribution of borehole/subsurface data. [21].Geostatistical Interpolation is applied within constrain defined by the geological boundaries identified with cognitive geological understanding.

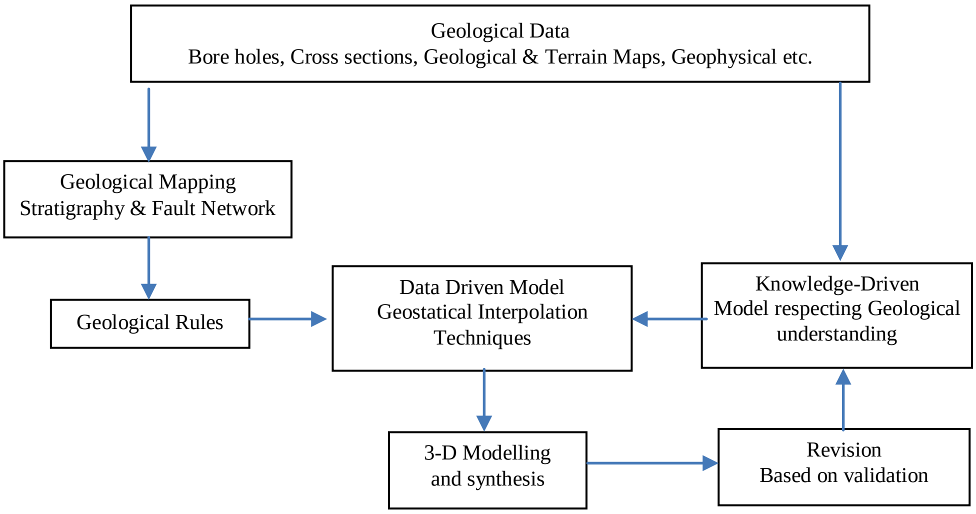

Fig.3. Combine Modelling Approach

IX. Validation of model

The density of drill-hole lithologic data is greatest at the surface, so resolution of the resultant model will be highest. When the solid lithologic model is trimmed with a DEM/ surface grid, the resulting upper model surface should compares to the geologic map. An initial test of the strength of the subsurface 3-D lithologic model is to compare the mapped surface geology to that predicted at land surface by the 3-D model [7]. The model simulated results should also be compared to the ''real-world scenario'' of the 3-D spatial model of the investigated site [30]. E.g., the evidence for validation of the modelling methodology for 3D modelling carried for the structure of the Chalk in the London Basin has come from chalk-cored boreholes from the Thames Waters Lee Tunnel and Thames Waters Ring Main extension, where site investigations suggest the presence of a major north south offset which has again been predicted by the model. In addition, a new hydrogeological model for London has found that in using the new fault model the resulting groundwater level pattern fits better [21].

An interactive comparison between modelled and measured potential fields provides a best-fit adjustment of the model geometry compatible with the different input data sets [15]. When discrepancies between computed and observed gravity fields are identified, the geology is locally reinterpreted. The model being interactively adjusted in 3-D. E.g. the 3-D gravity or magnetic contribution of the model can thus be calculated and compared to the measured potential fields for further interactive adjustment of the model geometry, to improve the accuracy of the geological model [15]. The result is a 3-D model that respects constraints imposed by geological and geophysical data and can be further use to interpret and discuss crustal scale structures [15].

X. Limitations of Modelling

Euro Conference in Spa, Belgium in [20], identified important impediments, at that time, to greater use of 3-D geological models:

- a lack of 3-D/4D mathematical, cognitive and statistical spatial tools;
- a lack of cheap modelling tools designed for the shallow subsurface that can be operated without specialist personnel
- the inability of models to depict natural variability of geological systems;

Very localized geological phenomena such as small scour hollows, relict pingo and allied periglacial structures and small channel infills cannot be easily shown at the intended resolution of the model unless a borehole proving the structure is included in a cross-section [16].

XI. Modelling Software.

The most common software packages used for building 3-D geologic maps and models in many geological survey organizations (GSOs) include, ArcGIS, Gocad, EarthVision, 3-D GeoModeller, GSI3-D, Multilayer-GDM, and Isatis. Many other software packages are also used in GSOs worldwide as part of modelling workflows, and these include software for GIS, geostatistical analysis, visualization, and property modelling [13]

The choice of 3-D modelling software and methodology used depends on many parameters such as required depth of the models, type of geological setting, geological context and degree of complexity of the geological objects. (e.g., karst, fault networks, dolerite intrusions, buried channels); need to mesh models for simulation; method to populate the models and the kind of properties needed for population; requirement for quantification of uncertainty [4]. Different 3-D modelling software packages are used to address different geological conditions and to satisfy other requirements such as quality and complexity of the initial data set and the final purpose of the model [4]. Approaches to geological modelling are different to suit the needs of individual GSOs (partly as a reflection of their customer base), which will likely remain the case in the foreseeable future. Convergence or streamlining of software use might occur over time, but it is impossible at present to envisage a standard piece of software, as this will intrude into individual organizational policies and culture, as well as the possible capabilities of clients [3]. Over time, common data formats and relevant standards should emerge, leading to increased interoperability and exchange [3].

11.1 Interface with other software

For pre-processing spatial data, calculating grids, or triangulating unevenly distributed data, (1) GIS tools (mainly ESRI products), (2) CAD programs such as MicroStation, or (3) interpolation software such as Surfer are applied.The geological structure in a GIS database is used to obtain an interface to numerical groundwater modelling tools such as Feflow or Modflow. These data are stored in GRID or point formats in ArcView. The GIS data management for all hydrogeological and hydrochemical data can be done with ArcView (ESRI). The geological cross-sections with their vertical 2D structure were held in a special tool for geological 3-D models. [30].The model can be used to generate synthetic cross-sections or borehole prognoses; or to generate files appropriate to displaying the component geological surfaces or shapes commonly used computer-assisted design (CAD) or geographic information system (GIS) software packages [14],[1].

The software being used have, common data formats interoperability and exchange capabilities. The specific engineering application and the multiple data with diverse quality and quantity may force to adopt combine use and integration of various software. This requirement may also lead to the new methodology, and new approach to data integration. The selected case studies from the various fields highlights the same.

Following are the commonly use 3-D geological modelling software and their modelling functionalities [13].

Table. 1. Software for 3D Geological Modelling

No	Software	Application
1.	**3-D GeoModeller** (Intrepid- French Geological Survey - BRGM)	• 3-D GeoModeller is “Geological editor” alternative to CAD or GIS, for helping to define complex 3-D geology. • Implicit modeling; geological thinking; accurate prediction of complex geological structure • 3-D GeoModeller allowed simultaneous data integration, synthesis, and geological interpretation of geophysical data in conjunction with 3-D geological mapping. • 3-D Geomodeller is based on an implicit modelling of surfaces where, each horizon is built by a 3-D interpolation function (potential field cokriging) that simultaneously account, for • Data points on horizon locations (Iso-potential values), - General orientations and polarities of structures (gradients), and existence of discontinuities (faults). - Full Tensor Inversion Gravity and Magnetic Modelling software to combine geological modelling and validation through geophysical inversion. - Geostatistics based model building with inherent *the uncertaintymeasures* in the model-building approach.
2.	**ArcGIS** (ESRI)	• Multi-source geological databases the effective organization and management of data. • To create additional input data for the modelling, including fault patterns, maps showing the extent of lithostratigraphic units, and other geological features • Analysis and interpolation of geological characteristics, • Assembling and visualizing 2-D maps and, for developing and visualizing

		3-D geological models (ArcScene). • Customized tools for 3-D geological modelling to create cross sections, make stratigraphic picks on 3-D boreholes, and generate surface maps of the tops or bottoms of map units. • 3-D GIS provide the tools for enabling interactive construction of volumetric models of the ground profile. These permit analysis and interpolation of geological characteristics, facilitating appraisal of the engineering problem. • With the aid of the powerful capability of data visualization, manipulation, sharing and editing.
3.	**Earth Vision** **(**Dynamic Graphics)	• High end 3-D geological modelling and visualization application • Data: 3-D passage points from boreholes, geological map, digitized cross sections, seismic data • Complex 3-D geometry and fault network representation • Spline type interpolation for layer-cake geometry, or 3-D function for 3-D objects • Modelling for oil and gas resources, mining applications, and surficial and near-surface geological mapping and modelling projects
4.	**Gocad (Geological Object Computer Aided Design)** (Paradigm Geophysical**.)**	• Gocad is a CAD system, with interpolation and surface fitting algorithms. • Use for visualization of 3-D models and inspection of 2-D surfaces. • incorporation of many data formats, integration of many workflows for reservoir engineering and advanced geological interpretation
5.	**GSI3-D (Geological SurveyingAnd Investigation In three dimensions)** (Hans-Georg Sobisch, British Geological Survey)	• GSI3-D is a methodology and associated software tool for 3-D geological modelling based on working practices of geologists- Cognitive modelling methodology/ Constructive method/knowledge-driven approach • GSI3-D is programmed to be part of a systematic, iterative, and interpretative geological mapping process. • Cross-section net- based interpolation • The functionality to model more complex bedrock environments.
6.	**Multilayer-GDM BRGM** (Geoscientific Data Model- French Geological Survey (Bureau de Recherches Géologiques et Minières):	• Suited for data control and for layered models with vertical faults with geostatistics application. • The Multilayer-GDM software utilizes BRGM's borehole and geological map data sets including fault traces, outcrop information, existing cross sections and outcrop-subcrop distributions, and a DEM. • The software performs consistency checks between these varied sources. • The model is controlled by a stratigraphic sequence with rules concerning the nature of bounding surfaces (e.g., erosional, on lap).
7.	**Isatis** (Geovariance)	• Advanced spatial and geostatistical analysis package that can be used for sophisticated spatial data analysis, geostatistical modelling and simulation, statistically based assessments of uncertainty, and 3-D visualization.Interfaces with standard 3-D geomodeling software • Statistical data analysis, semi-variograms, and interpolation facilities • 2D-3-D Simulation (facies simulation, pixel-based methods or object-based methods)
8.	**Rockworks** (RockWare)	• The geostatistical modelling packages, it interpolates surface and solid models, computes reserve and overburden volumes, and can display maps, logs, cross sections, fence diagrams, solid models, reports, and animations. • Supports wide range of 2-D and 3-D geological mapping and modelling techniques for visualizing, interpreting, and portraying surficial and subsurface information.
9.	**SKUA** (Paradigm Geophysics)	• Mapping in structurally complex geological settings where modelers can create grids consistent with true stratigraphy and structure while honoring data and geological rules.

10.	**Surfer** (Golden Software)	• The interpolation and visualization of 2-D surface models. Surfer has the capability to simultaneously view stacked sets of independent surfaces in 3-D space. • True stratigraphy and structure honoring data and geological rules.
11.	**Lynx** (Geoscience ModellingSystem)	• Using Lynx, data is stored in a 3-D database projected to user-selected planes to delineate polygonal boundaries of each geological unit. • These are connected by links to form solid volumes by interactive volume modelling
12.	**EVS/ MVS Environmental/Mining Visualization System** (C Tech. Development Corp.Kaneohe, HI)	• Geostatistics (Geostatistical Algorithm) based
13.	**Geophysical Data Analysis Software**	• Geostatistical Interpolation software to analyze geophysical data. • Examples Oasis montaj, GM-SYS (Geosoft), IPI2win, Geotools MT (AOA Geophysics, Inc.), and methods and software developed by the USGS etc.

XII. Conclusion

In spite of the limitations with 3-D modelling can prove to be the valuable tool for better geological understanding and related project decisions. Convergence of different modelling software capabilities, better data integration along with use of advance geostatistical techniques blended with cognitive knowledge are required to overcome these limitation. It has potential research element to modify the modelling approach. The knowledge gain through various case studies and associated research will definitely add to the 3-D geological modelling experience.

References

[1]. Aldiss D. T., Black M. G. et al. 2011. Benefits of a 3D geological model for major tunnelling works: an example from Farringdon, east–central London, UK ASIA GEOSPATIAL FORUM 2011**.**

[2]. Berg R. C., Mathers Stephen J., Kessler Holger, et al. 2011 Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations**.**

[3]. Berg Richard C., Mathers Stephen J., Kessler Holger, et al. 2011, Conclusions and Recommendations Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations**.**

[4]. Castagnac Claire, Truffert Catherine, Bourgine Bernard, et al. 2011.French Geological Survey (Bureau de Recherches Géologiques et Minières): Multiple Software Packages for Addressing Geological Complexities Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations.

[5]. Caumon Guillaume, 2010. Towards stochastic time varying geological modelling 2010 Mathematical Geosciences 42(5):555569.

[6]. Culshaw M.G. 2005. From concept towards reality: developing the attributed 3D geological model of the shallow subsurface(Quarterly Journal of Engineering Geology and Hydrogeology, 38, 231–284 1470-9236/05 $15.00 2005 Geological Society of London)**.**

[7]. Donald S. Sweetkind, Emily M. Taylor et al. 2010. Three-dimensional geologic modelling of the Santa Rosa Plain, California (Geosphere; June 2010; v. 6; no. 3; p. 237–274).

[8]. Elkadi A.S., Huisman M. 2002. 3D-GSIS geotechnical modelling of tunnel intersection in soft ground: the Second Heinenoord Tunnel, Netherlands**.**

[9]. Fallara F., Legault M. and Rabeau O. 2006. 3-D Integrated Geological Modelling in the Abitibi Subprovince (Québec, Canada): Techniques and Applications *Exploration and Mining Geology*; January 2006; v. 15; no. 1-2; p. 27-43.

[10]. Greg Keller, Gaywood Matile, Harvey Thorleifson. 2011. Manitoba Geological Survey: Multi-scaled 3-D Geological Modelling with a Single Software Solution and Low Costs, Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations**.**

[11]. Jacobsen Linda J., Glynn Pierre D., Phelps Geoff A., et al., 2011. U.S. Geological Survey: A Synopsis of Three-dimensional Modelling, Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations**.**

[12]. Kaufmann Olivier, Martin Thierry, 2008. Reprint of ''3D geological modelling from boreholes, cross-sections and geological maps, application over former natural gas storages in coal mines'' [Comput. Geosci. 34 (2008) 278–290].

[13]. Kessler Holger, Mathers Stephen J., Keefer Donald A., et al., 2011. Common 3-D Mapping and Modelling Software Packages, Synopsis of Current Three dimensional Geological Mapping and Modelling in Geological Survey Organizations.

[14]. Kessler, H., Mathers, S. & Sobisch, H.-G. 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. Computers and Geosciences, 35, 1311–1321.

[15]. Marteleta G., Calcagno P., Gumiauxb C., C. Trufferta. et al., 2004. Integrated 3D geophysical and geological modelling of the Hercynian Suture Zone in the Champ toceaux area (south Brittany, France) Tectonophysics 382 (2004).

[16]. Mathers S.J., Burke H.F., Terrington R.L., et al., 2014. A geological model of London and the Thames Valley, southeast England. Proceedings of the Geologists' Association 125 (2014) 373–382.

[17]. Neber A., Aubel J., Classon F., et al. 2006.From the Devonian to the present: Landscape and technogenic relief evolution in an urban environment IAEG2006 Paper number 517.

[18]. Ozmutlu enol, Hack Robert, 2003. 3D modelling system for ground engineering Springer-Verlag Berlin Heidelberg 2003.

[19]. Parry S., Baynes F. J., Culshaw M. G., et al. 2014. Engineering Geological Models – an introduction: IAEG Commission 25.

[20]. Rosenbaum & Turner 2003. EuroConference in Spa, Belgium.

[21]. Royse Katherine R. 2010. Combining numerical and cognitive 3D modelling approaches in order to determine the structure of the Chalk in the London Basin (Computers & Geosciences 36 (2010) 500–511).

[22]. Thierry Pierre, Marie Anne, Leparmentier Prunier et al. 2009. 3D geological modelling at urban scale and mapping of ground movementsusceptibility from gypsum dissolution: the Paris example (France) Engineering Geology 105 (2009) 51 –64.

[23]. Turner, 2006. Challenges and Trends for Geological Modelling and Visualization, Bulletin of Engineering Geology and the Environment, Volume 65, Number 2, May 2006, pp. 109-127.

[24]. Turner, A. K. Gable, C. (2007)."A review of geological modelling" In: Three-dimensional geologic mapping for groundwater applications, Workshop extended abstracts," Denver, Colorado (PDF).http://www.isgs.uiuc.edu/research/3DWorkshop/2007/pdffiles/turner.pdf .

[25]. Turner, A.K., [Editor] 1991. Three-dimensional Modelling with Geoscientific Information Systems. NATO ASI Series C: Mathematical and Physical Sciences, v. 354, Kluwer Academic Publishers, Dordrecht, the Netherlands, 443p.

[26]. Turner, & Dearman, W. R. 1980. The early history of geological models. Bulletin of the International Association of Engineering Geology, 21, 202-210.

[27]. Wang Yongzhi, Zhao Hui, Sheng Yehua et al. 2015. Construction and Application of 3D Geological Models for Attribute-oriented Information Expression Journal of Applied Science and Engineering, Vol. 18, No. 4, pp. 315322 (2015).

[28]. Williams, J., Scheib, A. 2008. Application of near-surface geophysical data in GSI3D: case studies from Shelford and Talla Linnfoots. British Geological Survey Open File Report (OR/08/068), 29pp. http://nora.nerc.ac.uk/5347/1/OR_08_068.pdf.

[29]. Wu Qiang, Xu Hua, Zou Xukai. 2005. An effective method for 3D geological modelling with multi-source data integration Computers & Geosciences 31 (2005) 35 – 43.

[30]. Wycisk P., Hubert T., Gossel W., Neumann Ch. 2009. High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial mega sites (Computers & Geosciences 35 (2009) 165 – 182).

[31]. Zhu Liang-feng, Li Ming-jiang, Li Chang-ling, et al. 2013. Coupled modelling between geological structure fields and property parameter fields in 3D engineering geological space Engineering Geology 167 (2013) 105–116.